HEAVY FUEL ENGINE TECHNOLOGY ASSESSMENT

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13. ABSTRACT (Maximum 200 words)

As part of the Military Single Fuel Forward logistics concept, all fuel-consuming equipment should be able to operate using JP-8. For most engine-driven equipment, this necessitates the use of diesel (compression ignition) rather than gasoline (spark ignition) engines. Because of the lower power density of diesel engines, especially small engines, some current fielded equipment, as well as new equipment being developed, are not complying with the Single Fuel Forward directives. The intent of this study was to survey existing state-of-the-art heavy fuel (diesel) engine technology and recommend an approach to DoD for the acquisition of JP-8 capable engines for these applications.

Equipment developers and item managers were surveyed to identify vehicles and equipment currently using gasoline engines, or situation in which engine limitations severely compromise developmental objectives. The characteristics of current state-of-the-art diesel engine technology, along with what might be achievable for military applications, were then compared with these requirements to determine what engine approaches might satisfy the equipment needs.

The final recommendation combines the following three steps to satisfy the requirements of the wide range of DoD engine applications: 1) Modify existing diesel engines to meet weight and power specifications to provide 10,000 DoD engines per year; 2) Design a new engine family utilizing commercial technology for most components to provide 33,000 DoD engines per year; 3) Design an engine family of very high power density to provide 1,000 engines per year that can not be produced by the other two steps.

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EXECUTIVE SUMMARY

Objective: There are several heavy fuel (diesel) engines needed for DoD applications, including engines for Unmanned Arial Vehicles (UAVs). The objective of this study was to identify the best approach to acquire those engines.

Importance of Project: The recommendations developed during this study are useful as a starting point for heavy fuel engine acquisition. This report contains a general description of the type of engine needed for each DoD application. The next step would involve the generation of specific program goals from the ideas presented here.

Technical Approach: Initially, several heavy-fuel powerplant options were considered: diesel engines, gas turbine engines, rotary engines and fuel cells. The diesel engine was chosen for further evaluation. Current state-of-the-art diesel engines were surveyed, as well as the specifics of current production models, and an approach was recommended for the acquisition of the needed engines.

Results: Compression ignition engines that satisfy all of the DoD engine needs can be obtained in three steps. Some of the engines can be modified production engines. Most of the engines must be obtained by development of a new four-stroke diesel engine family. This engine family can be based on existing commercial technology. To acquire a smaller number of DoD applications with strict power and weight requirements, a second family of engines can be developed. This family would consist of two-stroke diesels and would have a smaller commercial technology base. Included in this family are the UAV engines. It is estimated that the two engine families can be developed over a period of five years, at a funding level of $51,000,000.

TABLE OF CONTENTS

1. BACKGROUND AND OBJECTIVES 1

2. MOTIVATION 2

2.1 Logistical Considerations 2

3. APPROACH 3

4. POWERPLANT SPECIFICATIONS 3

4.1 DoD Requirements 3
4.1.1 Power Output 4
4.1.2 Specific Weight 4
4.1.3 Thermal Efficiency 4
4.1.4 Emissions 4
4.1.5 Costs 5

4.2 Powerplant Options 7
4.2.1 Spark-Assisted Diesel –Reciprocating or Rotary 8
4.2.2 Gas Turbine Engines 8
4.2.3 Diesel Engines 8
4.2.4 Fuel Cell 9

5. RESULTS AND CONCLUSIONS 9

5.1 Modified Commercial Diesel Engines 9
5.2 Commercially-Based Engine Family 11
5.3 DoD-Specific Engine Family 14

6. RECOMMENDATIONS 15

7. LIST OF REFERENCES 17

APPENDICES
A. Engine Duty Cycles
B. Basic Engine Calculations
C. Weight Breakdown of Cummins M11 Engine
D. Development of Commercially Based Engine Family
E. Current Diesel Engine Technology
F. Development of DoD-Specific Engine Family

LIST OF TABLES

1. DoD Applications for Heavy Fuel Engines 6
2. Powerplant Potential to Meet DoD Requirements 7
3. Existing Commercial Engines for Use in DoD Applications 11
4. Government Development Programs in Progress 12
5. Commercially-Based Engine Family, PNGV Power Section 13
6. DoD Specific Engine Family 15

LIST OF FIGURES

1. Development Program Outline 17

1. BACKGROUND AND OBJECTIVES

The Department of Defense requires a wide variety of engines to be used as powerplants for new or enhanced applications. In compliance with the "Single Fuel Forward" concept, these engines must operate on JP-8 or diesel fuel. The applications for these engines require small and lightweight power sources. This project involved a survey and analysis of state-of-the-art heavy fuel engine (HFE) technology. Heavy fuel engines identified by this study fulfilled a wide variety of requirements based on technical, cost, and logistical criteria. The result of this project is a strategy for acquiring the needed heavy fuel engines.

To gain information and insight into the HFE technology currently available, a Program Advisory Group (PAG) was established. This group consisted of recognized experts in vehicle fuels, diesel engine technology, and gas turbine engine technology. Additionally, the PAG received input from various industry and government sources. PAG membership consisted of the following:

<u>Defense Advanced Research Projects Agency</u>
John Gully, Chairman

<u>Office of the Secretary of Defense</u>
Joe Eash
John Fricas

<u>Department of Energy</u>
Bill Siegel

<u>Defense Airborne Reconnaissance Office</u>
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<u>NAVAIR</u>
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<u>NASA-Langley</u>
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2. MOTIVATION

2.1 Logistical Considerations

In 1988, the Department of Defense issued a directive (1)[1] stating that Military Services will develop and acquire new systems based only on diesel and turbine (JP-5/JP-8) fuels (2). This policy is part of the "Single Fuel Forward" concept of supplying only JP-8 fuels during overseas combat. The remaining gasoline engines within DoD combat and technical equipment require that a small amount of gasoline continue to be stocked, complicating the fuel supply process.

Aviation Gasoline (AVGAS) is particularly difficult to obtain. It is no longer stocked in the military system, so outside sources in the open market must continually be located. The quality of AVGAS locally purchased at various worldwide locations may vary, impacting engine operation. In addition, when AVGAS must be transported, the 55-gallon drum containers require special handling, from procurement to use and disposal. Special handling equipment (forklifts and fueler/defueler pumps) is required to move and transfer the fuel from the 55-gallon drums to support ground-based operations. The ability to transfer and move fuel (tankers, fuel bladders, and pumps) without possible contamination is impacted. Separate fuel pits are required to segregate the highly flammable fuel.

The low flashpoint of gasoline makes it readily flammable and explosive. This is especially dangerous at sea where a fire cannot be readily escaped. A special fuel bladder must be installed on ships to allow the gasoline to be stored outside the ship on a jettisonable rack. In case of fire, this bladder can be jettisoned, thereby reducing the danger of adding fuel to another fire or of the fuel igniting. However, once a bladder is jettisoned, there is no gasoline supply for further operations. The disposal of empty fuel drums, with the associated explosive hazard, is also difficult. Once all of these hazards

[1] Underscored numbers in parentheses refer to the list of references at the end of this report.

are considered, the ability to operate on JP-8 or JP-5 shipboard substantially increases handling safety.

3. APPROACH

The intent of this study was to survey existing state-of-the-art heavy fuel (diesel) engine technology and recommend an approach to DoD for the acquisition of JP-8 capable engines for these applications.

Equipment developers and item managers provided information on engines needed by DoD. They were surveyed to identify vehicles and equipment currently using gasoline engines or situations where engine limitations severely compromised developmental objectives. The characteristics of current state-of-the-art diesel engine technology, along with what might be achievable for military applications, were then compared with these requirements to determine what engine approaches might satisfy the equipment needs.

Initially, several heavy-fuel powerplants were considered, including gas turbine engines, diesel engines, spark-assisted diesel engines, and fuel cells. The potential for each powerplant to meet DoD engine needs was considered, and the diesel engine was determined to be the most suitable for the DoD applications. Diesel engine technology was then examined more closely, and an approach for the acquisition of the needed engines was developed.

4. POWERPLANT SPECIFICATIONS

4.1 DoD Requirements

This study targets 19 DoD engine applications that are either currently powered by gasoline-fueled, spark-ignition engines, or are new requirements. Specifications for the applications addressed in this study are listed in Table 1.

Some of these applications were developed around existing gasoline engines and require any replacement powerplant to have similar weight and size. Power output must be similar to avoid compromising performance. In all applications, fuel-consumption requirements have been set at or near the diesel state-of-the-art because of DoD 's objective to minimize the logistic burden of fuel supply.

4.1.1 Power Output

The applications listed in Table 1 require power outputs from 24 to 440 hp. In each case, the power requirement listed is the continuous power need. In the UAV cases, maximum power needs may be higher.

4.1.2 Specific Weight

The most significant characteristic of this set of applications is the required low weight per horsepower (specific weight), which ranges from 1.3 to 4.2 lb/hp. In almost every case, meeting the specific weight requirements requires pushing current technology to its limits.

4.1.3 Thermal Efficiency

All applications of Table 1 require a thermal efficiency greater than 35 percent, with the maximum requirement about 40 percent. These levels are within current diesel capabilities.

4.1.4 Emissions

Almost all of the applications listed in Table 1 are required to meet EPA emissions requirements for NOx, hydrocarbons, CO, and particulates. Those that aren't are limited in the amount of allowable visible smoke.

4.1.5 Costs

The needs addressed by this study comprise a relatively small number of powerplants; therefore, the unit cost promises to be high. The best solution to this problem is to identify commercial powerplants already in production that can be modified with relative ease to meet the DoD requirements. Failing this, the next best solution is to use the concept of "modularity," where a number of powerplants for different applications use a large number of common systems or sub-systems so that design, development, and production costs are reduced. An additional advantage of modularity is the reduction of replacement parts in inventory, which reduces logistical costs. A complete discussion of the cost savings possible through modularity can be found in "Cost Implications of a Common Engine." (3)

Table 1. DoD Applications for Heavy Fuel Engines

	Brake Power (hp)	Max. Eng. Wt. (lb)	Mission (hp-hr)	BSFC (lb/hp-hr)	Life (hr)	MTBCF (hr)	Duty Cycle	Smoke	EPA Emissions	Prod. Vol. (5 years)	Spec. Wt. (lb/hp)	Target Cost (1000 $)	BTE @ 100%
UAV*-High Endurance	120	200	1200	<0.45	500 TBO	2000	LD	Low	No	100	1.7	75	>31.4
UAV-Short Endurance	60	80	160	<0.45	250 TBO	1500	LD	Low	No	400	1.3	20	>31.4
RSTV†	136	300	1400	0.36	2000	1000	MD	Low	Yes	500	2.2	30	39.3
CHPS‡	300	700	2400	0.33	2000	1000	MD	Low	Yes	400	2.3	60	42.8
Motorcycle	40	75	80	0.38	1000	500	LD	Low	Yes	2000	1.9	5	37.2
Snowmobile	50	100	100	0.38	1000	500	HD	Low	Yes	2000	2.0	5	37.2
Outboard	50	100	200	0.38	1000	500	HD	Low	Yes	10000	2.0	5	37.2
Ship Fire Pump	30	45	50	0.4	200	100	LD	Med	No	750	1.5	5	35.3
Small Truck (hybrid)	136	300	200	0.38	2000	1000	MD	EPA	Yes	50000	2.2	6	37.2
Med. Truck (hybrid)	200	600	800	0.36	4000	2000	MD	EPA	Yes	2000	3.0	15	39.3
HMMVW**	180	450	800	0.38	2000	1000	MD	EPA	Yes	50000	2.5	10	37.2
FAV††	160	250	250	0.38	1000	500	HD	Low	No	100	1.6	15	37.2
RHIB‡‡ Boat	400	1200	1200	0.36	2000	1000	HD	Low	No	10000	3.0	35	39.3
APU***-10kW	24	95		0.4	4500	1500	HD	Low	Yes	(Total	4.0	3	35.3
APU-15kW	36	150		0.4	4500	1500	HD	Low	Yes	APUs	4.2	5	35.3
APU-30kW	66	200		0.4	18000	6000	HD	Low	Yes	req'd	3.0	6	35.3
APU-60kW	132	400		0.35	18000	6000	HD	Low	Yes	is	3.0	8	40.4
APU-100kW	220	700		0.35	24000	8000	HD	Low	Yes	90000)	3.2	12	40.4
APU-200kW	440	1500		0.35	24000	8000	HD	Low	Yes		3.4	15	40.4

*Unmanned Arial Vehicle
**High Mobility Multipurpose Wheeled Vehicle
***Auxiliary Power Unit
†Reconnaissance, Surveillance, Targeting Vehicle
††Fast Attack Vehicle
‡Combat Hybrid Power System
‡‡Rigid Hull Inflatable Boat

4.2 Powerplant Options

The powerplants evaluated were gas turbine engines, spark-assisted diesel engines (reciprocating and rotary), diesel engines, and fuel cells. The following criteria were used to evaluate the powerplants:

1. Is the best current technology capable of producing powerplants with operational characteristics reasonably close to DoD requirements?
   - Power Output
   - Specific Weight (lb/hp)
   - Thermal Efficiency
   - Emissions
   - Durability/Reliability
2. Can unit cost be reasonably close to DoD requirements?
3. Are commercial production powerplants available for any of the DoD applications?
4. Is the powerplant configuration amenable to modular construction?

Consideration of these questions is shown in Table 2.

Table 2. Powerplant Potential to Meet DoD Requirements

Can Target Be Met?	Gas Turbine	Spark-Assisted		Diesel	Fuel Cell
		Reciprocating	Rotary		
Power Output	Only for highest power needs	Yes	Yes	Yes	Only for Highest power needs
Specific Weight	Yes	Probably	Probably	Probably	No
Efficiency	No	Unknown	Unknown	Yes	Yes
Emissions	Yes	Very doubtful	Very doubtful	Yes	Yes
Durability/ Reliability	Yes	Unknown	Unknown	Yes	Yes
Commercial Production?	Only in high powers	No	No	Yes	No
Modularity Possible?	No	Yes	Yes	Yes	Maybe
Meet Cost Targets?	No	Maybe	Maybe	Maybe	No

The comments in Table 2 are, to some degree, subjective. An explanation of those comments follows.

4.2.1 Spark-Assisted Diesel – Reciprocating or Rotary

This engine has the ability to produce the required horsepower for the various DoD applications, but no previous design has proven that the specific weight, efficiency, emissions, or durability targets can be met. For instance, we believe that it would be very difficult to meet the emissions targets because of the primary need in this engine to coordinate spark and fuel injection. This coordination eliminates design flexibility needed for emissions control.

4.2.2 Gas Turbine Engine

Gas turbine technology is not available for the smaller power needs of the DoD. For the highest power needs, the specific weight targets can easily be met if the engine is not recuperated.[2] If it is, then the number of applications that can be satisfied are further decreased. According to turbine developers, full load efficiency targets can be met with recuperated engines, but part-load efficiency is not impressive and falls well under the diesel engine. There is little or no commercial production, and it is difficult to see how modular engines could be devised. There is no realistic indication that any of the cost targets can be met.

4.2.3 Diesel Engine

Power, efficiency, emissions, and durability targets can be met, and it appears from the following analysis that specific weight targets can also be met. A few engines that are close to the DoD requirements are commercially produced, and more importantly, commercial technology that can be applied directly to our problem is available from

[2] In a recuperated turbine engine, exhaust air is directed through a heat exchanger to raise the temperature of compressed intake air. Thus, energy in the exhaust is recirculated and conserved, and overall engine efficiency is increased.

many sources. Modularity is possible, and the cost targets can be met if full use is made of commercial production and technology.

4.2.4 Fuel Cell

The PAG did not encounter any viable fuel cells that could be produced to burn JP-8 and diesel fuel. Very low-power fuel cells seem unlikely, but the highest DoD power needs could probably be satisfied. However, current technology offers no possibility of meeting the specific weight requirements, although (given a large and heavy fuel cell and successful heavy fuel technology) the requirements for efficiency, emissions, and durability could probably be met. Given the lack of commercial experience and technology, it seems unlikely that the cost targets could even be approached.

5. RESULTS AND CONCLUSIONS

For the reasons discussed in Section 4, the diesel was selected as the powerplant to satisfy the DoD requirements, and no further consideration was given to the other powerplant types.

5.1 Modified Commercial Diesel Engines

To find existing commercial engines that might fit a DoD application, Southwest Research Institute's Engine Research Database as well as Power Systems Inc.'s EnginLink database were used. Both of the databases contained detailed and up-to-date specifications for the majority of the compression-ignition engines that are manufactured worldwide. Upon comparison of the two databases, it was found that they contained similar information with few minor differences.

The engine database was searched to find existing engines that matched the specifications set for each of the DoD applications in Table 1. The following fields were used to determine whether or not an engine "matched": output power, engine weight, and duty

cycle. If an existing engine had at least 75 percent of the specified output power, less than 133 percent of the specified engine weight, and the same (or a more severe) duty cycle as the DoD applications, it was considered to be a match for that application. For an explanation of duty cycle requirements, see Appendix A. By using those search criteria, three commercial engines were identified. Each of these engines had lower power and greater weight than required by DoD. The possibility of making modifications to these engines so that they would meet the specifications was then considered. Only three matches were found because 1) commercial engines were heavier than DoD requires, 2) few manufacturers produce diesels in the power range needed, and 3) of those that were found in the right power range, many were light-duty engines, and a heavy or medium duty engine is often required.

Power output can be increased with increased turbocharging. It was estimated that the maximum power increase is approximately 25 percent[3]. This value was chosen using experience with the effects of power increase on engine life and durability.

Weight can be reduced by the use of lighter materials. For a commercial engine with cast iron cylinder block and heads, the weight reduction that can be achieved by substituting aluminum block and heads is approximately 22 percent. If the engine has a cast iron block but aluminum heads, the weight reduction is about 16 percent. These weight reduction estimates are based on the analysis of the weights of the components of a Cummins M11 diesel engine (details are presented in Appendix C).

It was found that modified commercial engines could replace only the 15, 100, and 200 kW Auxiliary Power Unit (APU) engines. The requirement for these three applications is 10,000 engines per year. The specifications for these engines and the modifications that would be required are shown in Table 3. An American manufacturer makes only one of these engines.

[3] If the Brake Mean Effective Power (BMEP) of that engine were already above 200 psi, it would not be safe to boost it by the full 25 percent. For an explanation of the relationship between BMEP and output power, see Appendix B.

Table 3. Existing Commercial Engines For Use in DoD Applications												
Engine Mfg.	**No. of Cyl**	**Bore (in)**	**Stroke (in)**	**Disp (in^3)**	**Pwr (hp)**	**RPM**	**BMEP (psi)**	**Wt. (lb)**	**Spec. Wt. (lb/hp)**	**Duty Cycle**	**Wt. De-crease**	**Power In-crease**
APU-15kW					36			150	4.17	HD		
Kubota V800-TB	4	2.52	2.44	49	34	4500	122.6	165	4.85	HD	9.1%	5.9%
APU-100kW					220			700	3.18	HD		
Navistar T444E	8	4.11	4.18	444	215	3000	127.9	930	4.33	HD	24.7%	2.3%
APU-200kW					440			1500	3.41	HD		
Iveco AIFO 8460.41	6	4.72	5.51	580	370	2100	240.8	1900	5.13	HD	21.0%	18.9%

Although these three engines already exist, there would be some technical risk in modifying them to the degree required. Increasing the power output (and therefore the cylinder pressure) of an engine will increase the stress on that engine during operation, and reduce its durability. Durability is reduced again by the substitution of light components for heavier ones. However, these engines will be used as powerplants for APUs, which require engines with long life. Substantial development work will be required to make substantial power and weight changes without affecting durability.

5.2 Commercially Based Engine Family

Modified commercial engines can only be used for three of the 19 DoD applications. To fulfill the engine requirements of the other 16 applications, new engines will have to be developed. In compliance with our objectives, the PAG focused on the development of a single engine family to satisfy as many of the DoD requirements as possible.

Several diesel engine development programs sponsored by different government and industry groups are currently in progress (Table 4). The small, high-power-density diesel engines that result from these programs will have power sections that are candidates for a modular engine family.

Table 4. Government Development Programs in Progress						
Program Name	Sponsor	Contractors	Power Level (hp)	Power Density (lb/hp)	Funding Level	Completion Year
Sport Utility Vehicle	DOE & Industry	Caterpillar, Cummins, DDC	200-250	2.5	$165 M 5 years	2002
Partnership for a New Generation of Vehicles	DOE & Industry	Ford, GM, Chrysler	60-90	2	$100 M 5 years	1998
General Aviation Program	NASA & Industry	Teledyne Continental	200	<1.5	$1.9 M 3 years	2000
UAV Exploratory Development	DARO	ECA, FEV, 6A	120-160	1-1.5	$2 M	1998

If the cylinder bore diameter of the power cylinder of an engine family is known, as well as the rated piston speed and the engine weight per unit volume of piston displacement, the power and weight characteristics of an entire modular engine family can be determined. In the interest of utilizing commercial components and technology, the power cylinder of the DoD engine family was chosen from among the engines of Table 4. The third and fourth engines listed in this table were eliminated from consideration because they both employ two-stroke cycles for which little commercial production or technology exists. The remaining two (the SUV and PNGV) were evaluated as modular engine family candidates, because they are four stroke engines using state-of-the-art technology for high efficiency, emissions control, and lightweight. The PNGV engine was determined to be the better candidate, primarily because of its smaller bore diameter (estimated as 3.01 in.), which results in a lower specific weight than the SUV engine (with a bore diameter of 3.8 in.). Details of the assumptions and calculations used to project engine family characteristics are presented in Appendix D.

Rated piston speed of the PNGV engine is estimated to be 2300 fpm. While the PNGV engine is not yet designed, state-of-the-art, high-speed, direct-injection (DI) diesel engines can achieve a volume-specific weight of 1.9 pounds per cubic inch of displacement, as found in our databases, if aluminum blocks and head are used. The volume-specific weight is largely independent of the number of cylinders and is an

attribute of the engine design, including the power section design. Therefore, all the engines in a modular family will have the same volume-specific weight, which in this case is 1.9 lb/in^3.

It was found that a modular engine family with a 3.01 in. cylinder bore diameter, a piston speed of 2300 fpm, and a volume-specific weight of 1.9 lb/in^3 would satisfy 13 of the remaining 16 DoD applications. This amounts to the production of 33,000 engines per year. As can be seen from Table 5, this engine family would range in power output from 24 to 400 hp, and in specific weight from 1.2 to 3.7 lb/hp. These are very low weight-to-power ratios. Currently, the specific weight is no lower than 2.8 lb/hp in the most advanced commercial engines. Information on current commercial diesel engine technology can be found in Appendix E. However, at the rated horsepower, the Brake Mean Effective Pressure (BMEP) of some of the engines in this modular family must be as high as 270 psi to produce the specific weight shown in Table 5. If the BMEP of an engine in this family is lowered while maintaining the specification power level and using the modular power section, the number of cylinders must be increased. This will increase the specific weight (lb/hp).

Table 5. Commercially-Based Engine Family, PNGV Power Section

Application	Output Power (hp)	Number of Cylinders	BMEP (psi)	Specific Weight (lb/hp)
UAV-High Endurance	120	4	245	1.34
RSTV	136	5	220	1.46
CHPS	300	10	240	1.34
Snowmobile	50	2	200	1.64
Outboard	50	2	200	1.64
Small Truck (hybrid)	136	5	220	1.46
Medium Truck (hybrid)	200	6	270	1.22
HMMVW	180	6	240	1.37
FAV	160	5	260	1.26
RHIB Boat	400	12	270	1.24
APU-10kW	24	2	95	3.65
APU-30kW	66	3	180	1.82
APU-60kW	132	5	215	1.56

In order to realize the specifications of Table 5, this modular engine family must incorporate state-of-the-art technology relating to all aspects of the diesel engine. This would include:

- Four valves/cylinder
- High pressure, common rail fuel injection
- Highly developed air/fuel mixing
- Turbocharged and intercooled
  - Variable geometry turbocharger
- Light alloy components (cylinder head, block, rods and housings)
- Low friction valve gear
- Reduced heat flow to coolant
- Exhaust aftertreatment and EGR, depending on turbine emissions standards

5.3 DoD-Specific Engine Family

The three DoD applications remaining (Short Endurance UAV, Motorcycle, and Ship Fire Pump) cannot be satisfied by either a modified commercial engine or the commercially based engine family. These applications have low power requirements as well as very low specific weight requirements, which could not be obtained with the commercially based power section.

The low specific weight of the remaining three DoD engine applications suggests a two-stroke diesel cycle rather than a four-stroke. The two-stroke engine has long been a recognized solution for UAV and motorcycle applications. Various two-stroke cylinder sizes were investigated. The rated piston speed was taken as 2300 fpm. Liquid cooling was chosen for this family, because it is believed that the higher BMEP possible with liquid cooling will more than offset the weight penalty (about 0.2 lb/hp) associated with coolant, radiator, fan (not required in the UAV), and coolant pump. It was estimated that the volume-specific weight can be as low as 1.42 lb/in^3 displacement, therefore this was the value chosen. This power section is not, nor probably ever will be, commercially designed and is therefore a "DoD-Specific" power section.

Table 6 shows the resulting engine family. To insure that both UAV engines in the DoD requirements have a large degree of commonality, the High Endurance UAV engine (which was originally included in the commercially based engine family) was moved over into the DoD-Specific family.

Table 6. DoD-Specific Engine Family				
(2-stroke DI diesel, 2.75 in. bore diameter, 2300 fpm piston speed, 1.42 lb/in^3 disp.)				
Application	Output Power (hp)	Number of Cylinders	BMEP (psi)	Specific Wt. (lb/hp)
UAV-High Endurance	120	3	195	0.59
UAV-Short Endurance	60	2	145	0.75
Motorcycle	40	2	100	1.12
Ship Fire Pump	30	2	75	1.50

There are only two engines in this engine family, a two-cylinder and a three-cylinder. The total yearly number of engines required from this family is less than 1,000. Power output for the engines ranges from 30 to 120 horsepower. The specific weights that result from combining these engines into a family are very low, dropping to 0.6 lb/hp for the High-Endurance UAV. These low specific weights might be questioned. If so, two factors should be analyzed for feasibility: the BMEP used for the specific engine under scrutiny and the volume-specific weight (1.42 lb/in^3) used for all the engines. At the same time, the small bore diameter makes lower specific weights possible. As bore diameter decreases at a constant piston speed, the engine speed (RPM) increases and specific weight (lb/hp) decreases. In other words, to obtain a given power with the minimum weight at a given BMEP, reduce the bore diameter and increase the number of cylinders.

6. RECOMMENDATIONS

In order to obtain heavy fuel engines that meet the specifications of all of the DoD applications in Table 1, it is recommended that the following three steps be taken:

Modify Existing Commercial Engines

- Three DoD applications satisfied by this step
- 10,000 engines per year
- Modifications feature reduced weight and increased power
- Durability may be reduced
- Relatively low cost and low risk

Develop a Commercially Based Engine Family

- 12 DoD applications satisfied by this step
- 33,000 engines per year
- Commercially based power section common to all family members
  - Common fuel injection and power section
  - Number of cylinders different for different power needs
- Technical goals:
  - Engines will have specified specific weight (1.2 to 3.7 lb/hp)
  - Thermal efficiency greater than 40%
  - More than 40% of engine from commercial components
- Will meet emissions requirements

Develop a DoD-Specific Engine Family

- Four DoD applications satisfied by this step
- Less than 1,000 engines per year
- Required for highest power density needs, including UAV's
- Modular family with common power section
- Technical goals:
  - Engines will have less than 1.5 lb/hp
  - Thermal efficiency of 40%
  - About 20% of engine from commercial components
- High cost and high risk

These three steps are independent. However, the development of a commercially based engine family would benefit from waiting until completion of the other government engine-development programs in progress. The new technology developed in those programs will help reduce the cost and risk of the development work of the commercially based engine family. It is recommended that development of the DoD-specific engine family be undertaken first. A recommended development program outline is shown in Figure 1.

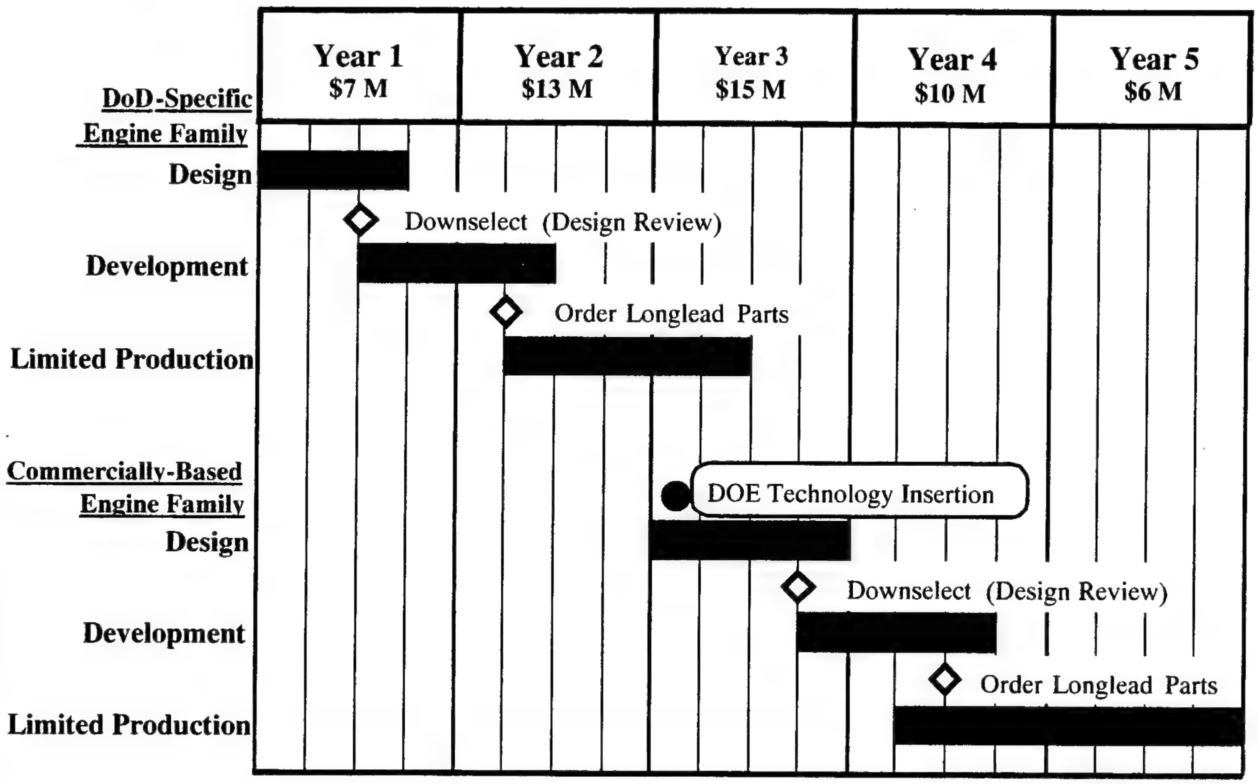

Figure 1. Development Program Outline

7. LIST OF REFERENCES

1. Department of Defense Directive 4140.43, subject: "Fuel Standardization," March 1988.

2. Military Specification MIL-T-83133C, "Turbine Fuels, Aviation Kerosene Types," NATO F-34 (JP-8) and NATO F-35, 22 March 1990.

3. TACOM Cost Analysis Division, "Cost Implications of a Common Engine"

APPENDIX A
Engine Duty Cycles

Engines can be divided into one of three categories based the duty cycle they were designed for. If a light duty engine were used in an application that required it to operate under a medium or heavy duty cycle, the life of the engine would be significantly shortened.

- Light Duty (LD) Engines:
  - Mostly used in automobile service
  - Spend 80% of life below 50% power
  - Less than 1% of life spent at full load

- Heavy Duty (HD) Engines:
  - Commercial truck, marine, and genset applications
  - 80% of life spent above 50% power
  - 10% of life spent at idle

- Medium Duty (MD) Engines:
  - Between light and heavy duty engines

APPENDIX B
Basic Engine Calculations

Common variables:

BMEP	Brake Mean Effective (Cylinder) Pressure
P	Brake horsepower (bhp)
N	Rotational Speed of Crankshaft (RPM)
V_D	Volume Displacement of engine (in³)
M	Weight of Engine (lb)
n_s	Revolutions per Cycle (1 for 2-stroke engines, 2 for 4-stroke engines)
S_p	Piston Speed (fpm)
S_t	Piston Stroke (in)
SW	Specific Weight of Engine (lb/hp)
VSW	Volume Specific Weight of Engine (lb/in³)

Relationship between BMEP, power, engine speed, and displacement:

$$BMEP = \frac{P \times 396{,}000 \times n_s}{V_D \times N} \qquad (1)$$

Piston Speed:

$$S_p = \frac{S_t \times N}{6} \qquad (2)$$

Specific Weight of Engine:

$$SW = \frac{M}{P} \qquad (3)$$

Volume Specific Weight of Engine:

$$VSV = \frac{M}{V_D} \qquad (4)$$

BMEP using specific weight and specific volume:

$$BMEP = \frac{VSW \times 396{,}000 \times n_s}{SW \times N} \qquad (5)$$

APPENDIX C
Weight Breakdown of Cummins M11 Engine

A Cummins M11 Engine was torn down and each component weighed. Calculations were done to determine the weight savings possible by substituting lighter materials for some of the heavier components, including the cylinder block and heads, rods, and housings. The criterion for material substitution was that the original stiffness of the component be maintained.

The original and modified weights of the components of the M11 engine are shown in the Table C-1 below.

Table C-1. Potential Weight Modifications of Cummins M11 Engine

Component	Original Weight (lb)	Modified Weight (lb)
Cylinder Block	492	261
Cylinder Head	228	121
Housings	184	98
Rods	56	44
Crankshaft	235	Not modified
Camshaft	57	Not modified
Pistons	40	Not modified
Valves & valve gear	94	Not modified
FIE & drive gear	66	Not modified
Cylinder liners	71	Not modified
Flywheel	86	Not modified
Wrist pins	18	Not modified
Bearings and caps	48	Not modified
Balancer	32	Not modified
Gears & pulleys	29	Not modified
Brackets, supports, & bolts	39	Not modified
Coolant filter,hsg,thermostat,pump	86	Not modified
Oil cooler, filter, & oil pump	53	Not modified
Turbocharger & manifold	64	Not modified
Control module	11	Not modified
Starter	39	Not modified
TOTAL	**2028**	**1592**

It was found that a 22-percent weight reduction could be achieved if the engine's largest cast iron and steel components were converted to aluminum and titanium. If the cylinder head of the engine had already been made of aluminum, only a 16-percent total weight reduction would have been possible. The weight reduction is shown graphically in Figure C-1 below.

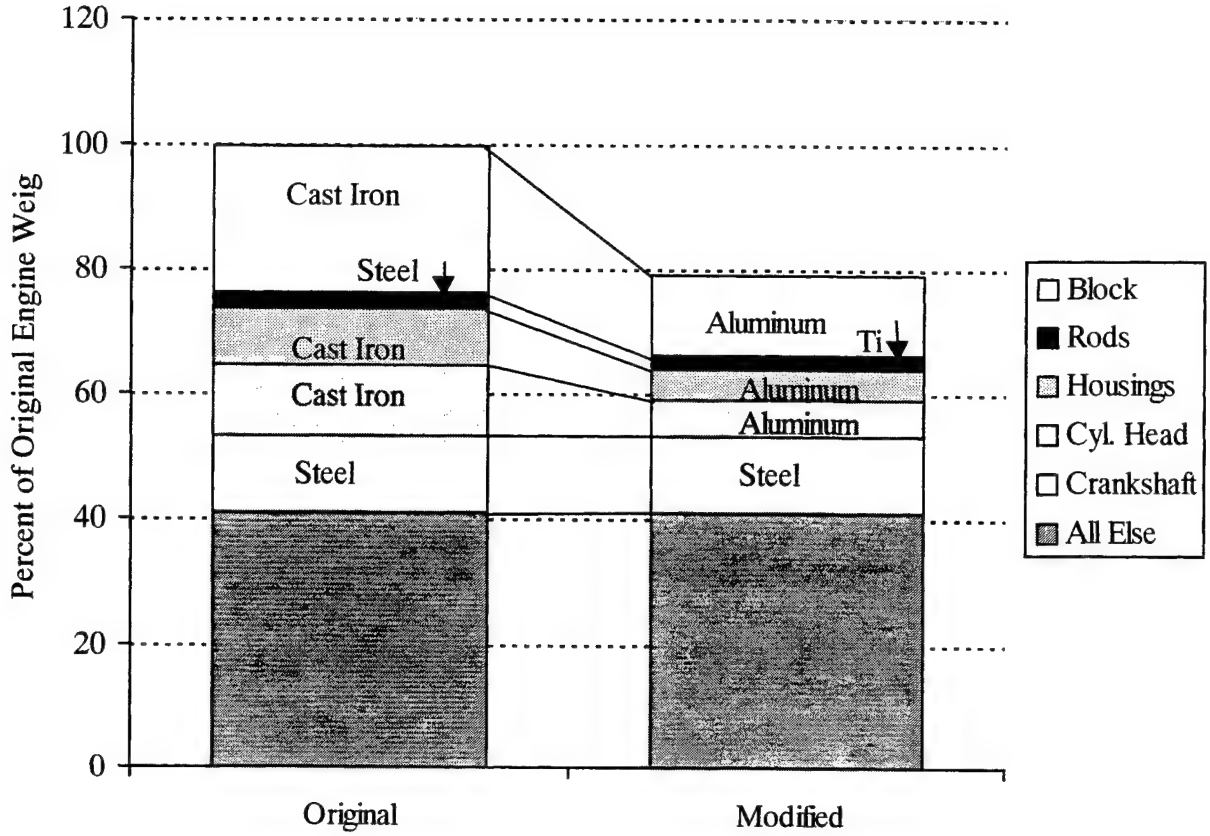

Figure C-1. Weight Reduction of Cummins M11 Engine

APPENDIX D
Development of Commercially Based Engine Family

An engine family consists of several engines with the same power section (cylinder, piston, head, connecting rod, fuel-injection equipment) but differing numbers of cylinders. The output power from different numbers of cylinders was determined using Equations (1) and (2) from Appendix B.

The bore diameter designed for the family was estimated from PNGV preliminary design data. A piston speed of 2300 feet per minute and a bore/stroke ratio of 1 were assumed. The engine has a four-stroke cycle. This information was used to develop the following plot.

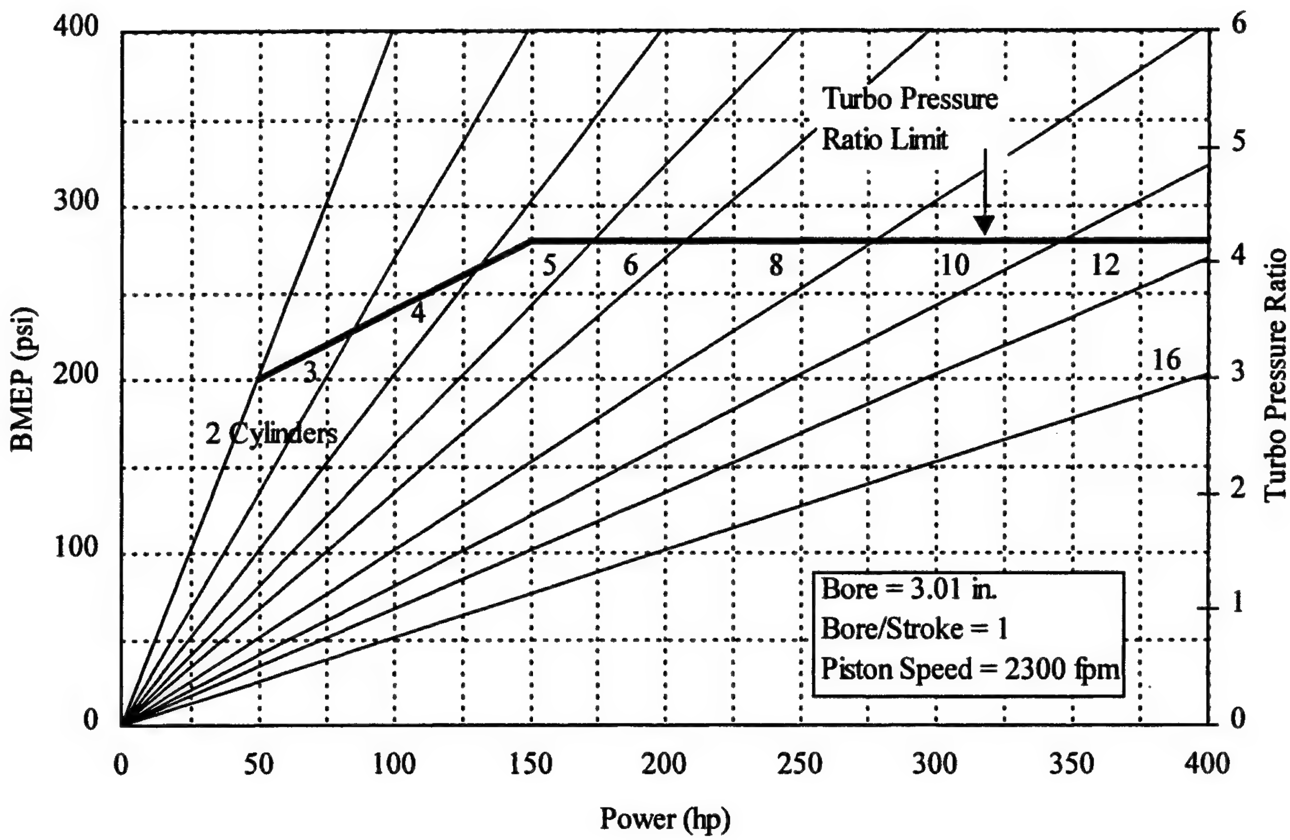

Figure D-1. <u>Plot of Commercially Based Engine Family</u>

This plot can be used to determine the number of cylinders and BMEP required to develop the horsepower output for each DoD application. BMEP is limited by the maximum available turbocharger pressure ratio, which is also shown on the plot. For example, if a 150 hp engine is needed, enter the horizontal axis at 150 hp and move vertically upwards. Intersections with the slanted lines define engine configurations that will produce 150 hp: 16 cylinders at 75 psi BMEP, 12 cylinders at 100 psi BMEP, 10 at 120, 8 at 150, 6 at 200, and 5 cylinders at about 245 psi BMEP. One cannot exceed the

BMEP defined by the turbo pressure limit. All of these engines are solutions, but the lightest engine is the one at the highest BMEP. In the report, all of the engines chosen for the family are those with the highest BMEP. If BMEP levels chosen for any particular engine are thought to be excessive, the BMEP can be decreased and the number of cylinders increased, and the engine weight will increase.

In the table below, the number of cylinders and maximum BMEP is shown for the 16 DoD applications not satisfied by commercial engines.

Table D-1. Commercially-Based Engine Family

	Specified Power (bhp)	Specified Specific Wt. (lb/hp)	Resulting No. of Cyl.	Resulting BMEP (psi)	Resulting Specific Wt. (lb/hp)
UAV-High Endurance	120	1.67	4	245	1.34
UAV-Short Endurance	*60*	*1.33*	*3*	*165*	*1.99*
RSTV	136	2.21	5	220	1.46
CHPS	300	2.33	10	240	1.34
Motorcycle	*40*	*1.88*	*2*	*165*	*1.99*
Snowmobile	50	2.00	2	200	1.64
Outboard	50	2.00	2	200	1.64
Ship Fire Pump	*30*	*1.5*	*2*	*125*	*2.63*
Small Truck (hybrid)	136	2.21	5	220	1.46
Medium Truck (hybrid)	200	3.00	6	270	1.22
HMMVW	180	2.50	6	240	1.37
FAV	160	1.56	5	260	1.26
RHIB Boat	400	3.00	12	270	1.24
APU-10kW	24	3.96	2	95	3.65
APU-30kW	66	3.03	3	180	1.82
APU-60kW	132	3.03	5	215	1.56

For each application, *BMEP* and *N* (from piston speed and stroke) are known. The minimum feasible volume-specific weight, VSW, was estimated from data on commercial diesel engines (see Appendix E). Equation (5) from Appendix B was then solved for specific weight. In three cases in the table above (italicized), the specific weight of our engine design is higher than the DoD-specified value. Therefore, these three engines will not fit into this engine family.

APPENDIX E
Current Diesel Engine Technology

Commercial engine data from two databases was used throughout this project. The first database was developed by the SwRI Engine Design Department. Data from the second was commercially available to SwRI from Power Systems, Inc. The data was used to find commercial engines that could be modified to fit DoD applications. It was also used to gain insight into engine characteristics of today's diesel engines.

The following plots were developed as tools for analyzing the data. All engines with bore diameters less than 3.5 in. are plotted; larger engines were not plotted because they are too large to be relevant to this study. Following the plots is a table with information relating to some of the most notable engines shown on the plots.

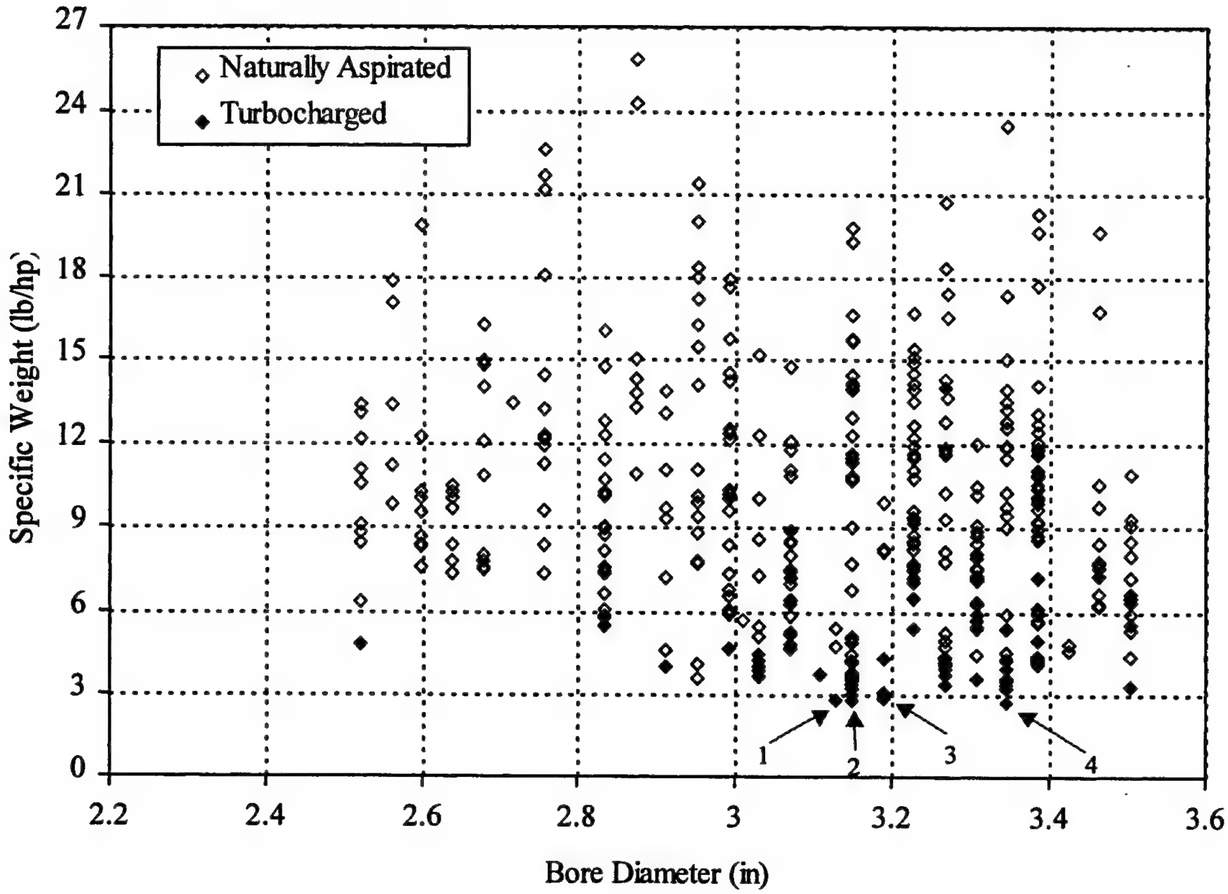

Figure E-1. Specific Weight vs. Bore Diameter

From this plot, it was determined that the minimum specific weight available in a commercial engine is 2.8 lb/hp. In Table E-1, engines 1 and 3 from the plot above are listed as having aluminum cylinder heads. If light alloys were also used for the cylinder block, housings, and rods, a 16-percent weight reduction would be possible. Additionally, with additional turbocharging, the power output could be increased by 25 percent. Overall this leads to a 1.9 lb/hp minimum achievable specific weight. The cylinder head material of engines 2 and 4 is not known. If it is cast iron, the weight reduction can be 22 percent, resulting in a specific weight of 1.7 lb/hp

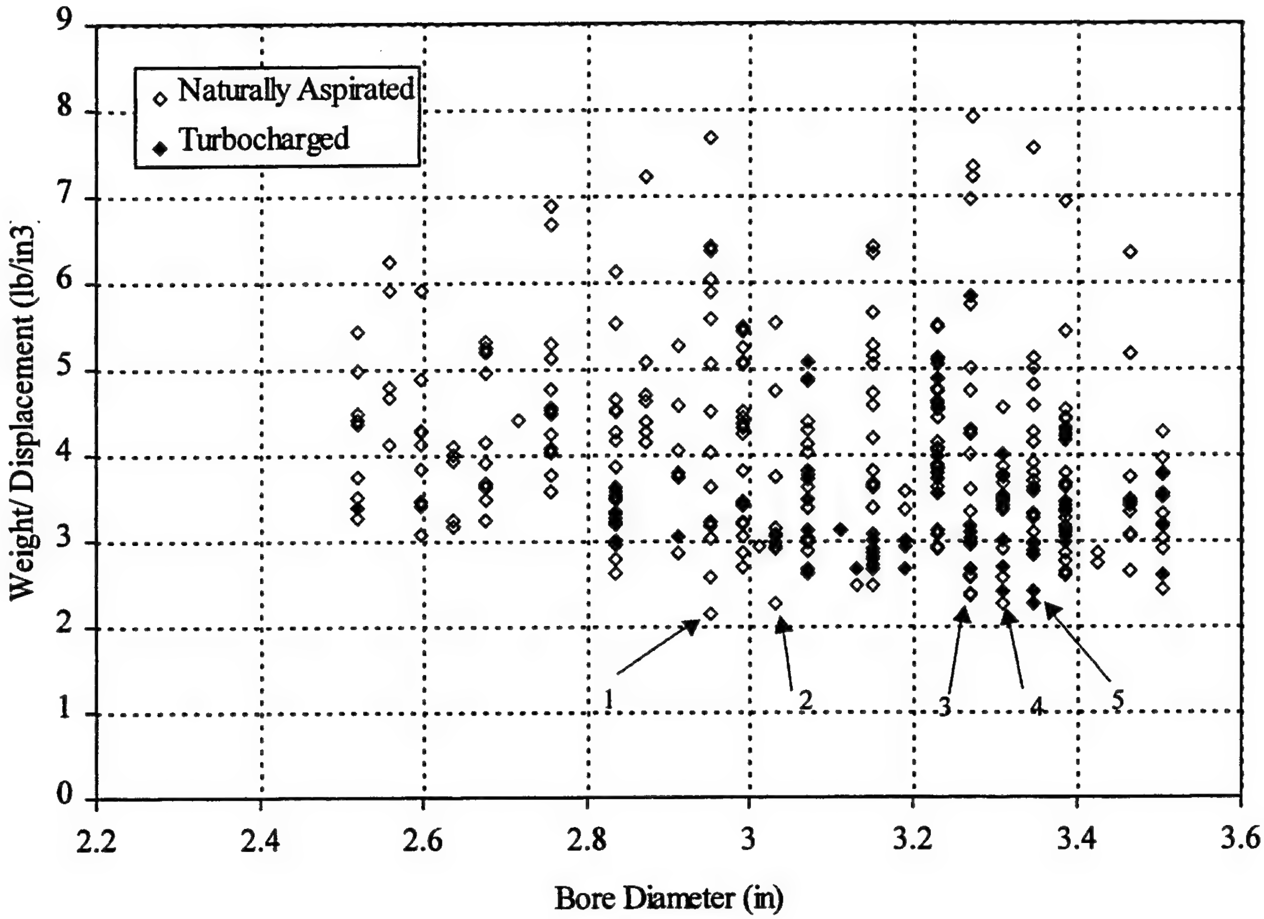

Figure E-2. Volume-Specific Weight vs. Bore Diameter

This plot was used to determine the minimum volume-specific weight that is currently available commercially; i.e., 2.3 lb/in^3. However, with a 16-percent weight reduction (for an engine that already has an aluminum cylinder head), this could be reduced to 1.9 lb/in^3. With a 22-percent weight reduction (for an engine that has a cast iron cylinder head), this could be reduced further to 1.7 lb/in^3.

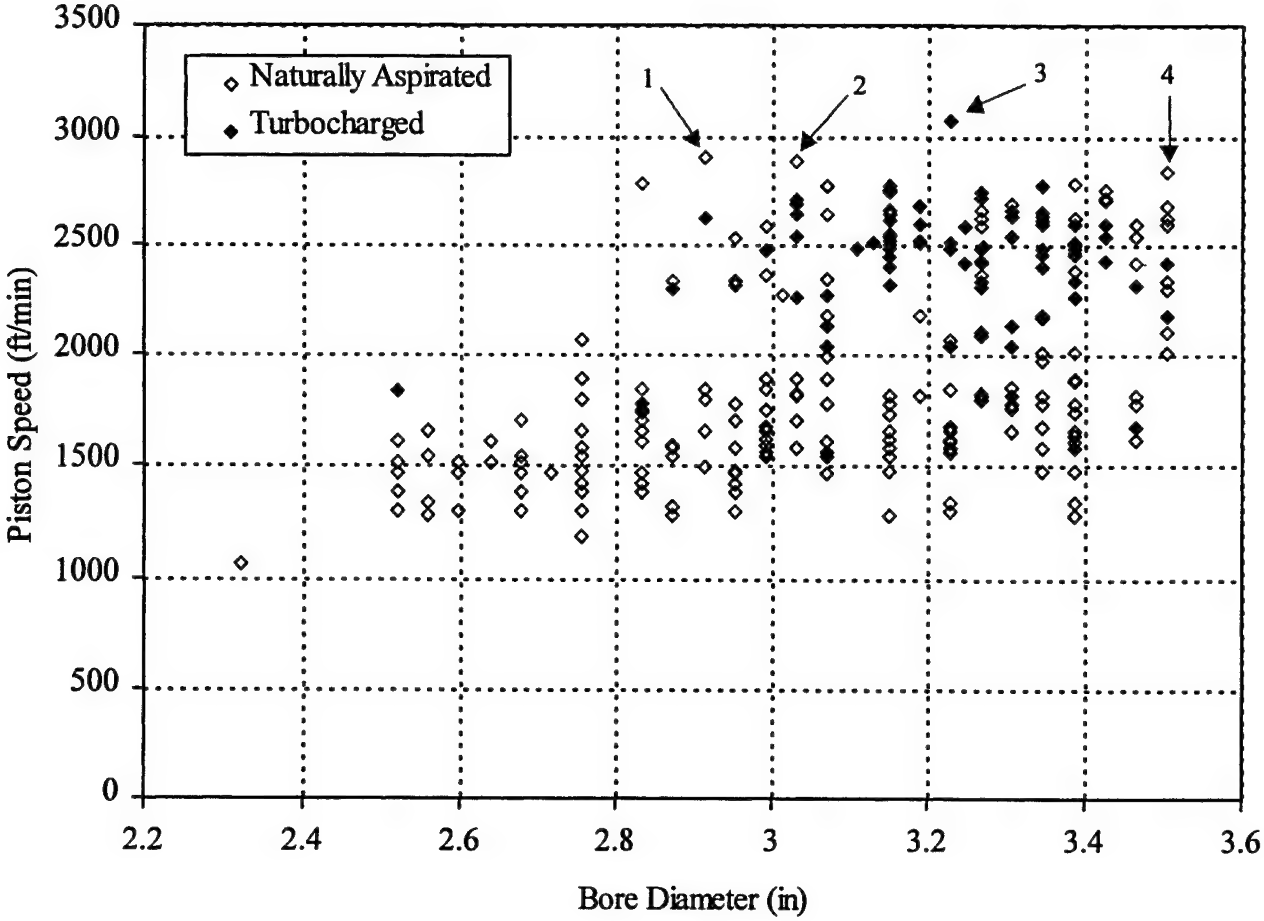

Figure E-3. Piston Speed at Rated Horsepower vs. Bore Diameter

This plot was used to determine feasible piston speeds. These engines reach speeds up to 2800 fpm (not counting a few anomalous points). Nevertheless, we chose a value of 2300 fpm for our engine families for some margin in durability.

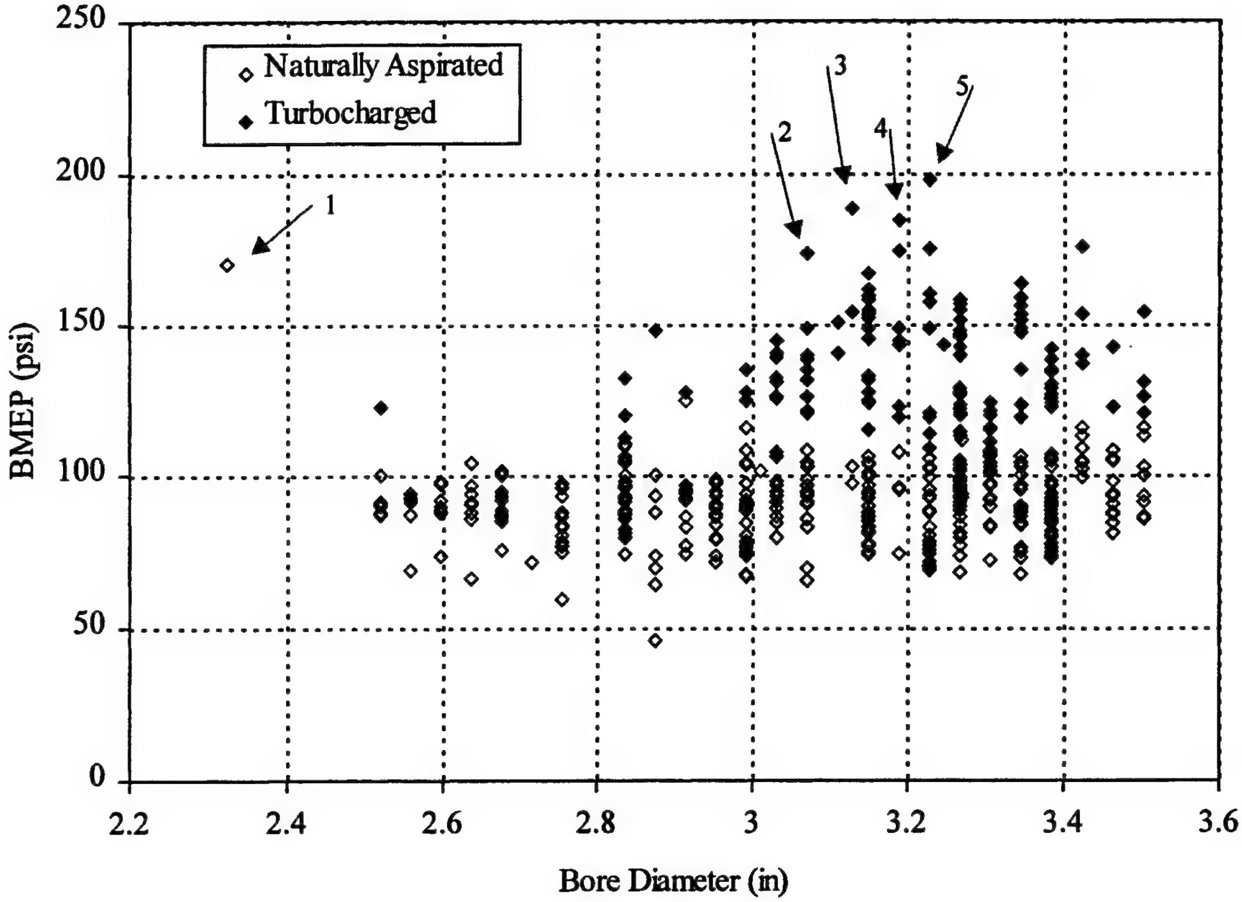

Figure E-4. Brake Mean Effective Pressure (BMEP) at Rated Horsepower vs. Bore Diameter

This plot shows that at rated horsepower, the BMEP of most diesel engines is less than 150 psi, although there are some engines with higher BMEP's, ranging from 150 to 180 psi.

Table E-1. Information on Notable Engines of Previous Plots

No. on Plot	Engine Mfg.	Model	Spec. Wt. (lb/hp)	Spec. Vol. (lb/in3)	Cyl.	Bore (in)	Displ. (in3)	Power (hp)	RPM	BMEP hp (psi)	Asp	Wt. (lb)	Piston Speed (fpm)	Cyl. Head Mat.
	Engines with Low Specific Weight:													
1	Volkswagen	1.9L	2.8	2.7	4	3.13	115.7	110	4000	188	T	309	2507	Al.
2	BMW	M51D25	3.0	2.8	6	3.15	152.6	143	4800	155	T	434	2614	
3	Volkswagen	2.5L	2.9	2.7	5	3.19	150.2	140	4000	185	T	401	2507	Al.
4	Rover Cars	2.0L	2.8	2.4	4	3.35	121.4	105	4200	163	T	291	2453	
	Engines with Low Specific Volume:													
1	Peugeot SA	TUD3	3.6	2.1	4	2.95	83.0	50	5000	95	N	178	2525	
2	Peugeot SA	TUD 5	4.0	2.3	4	3.03	99.9	56	5000	89	N	226	2883	Light
3	Peugeot SA	XUD 9	4.3	2.4	4	3.27	116.6	64	4600	95	N	276	2656	
4	Perkins	Prima 65	4.5	2.3	4	3.31	121.4	62	4500	90	N	276	2628	
5	Rover Cars	2.0L	3.2	2.3	4	3.35	121.4	85	4500	123	T	275	2628	
	Engine with High Piston Speeds (at Rated Horsepower):													
1	Toyota	1 N	4.6	2.8	4	2.91	89.1	55	5200	95	N	254	2903	
2	Peugeot SA	TUD 5	4.0	2.3	4	3.03	99.9	56	5000	89	N	226	2883	Light
3	Fiat	1.9L			4	3.23	116.1	134	5200	175	T		3071	
4	Mercedes	OM 604			4	3.50	131.2	94	5000	113	N		2842	
	Engines with High BMEP (at Rated Horsepower):													
1	Kirov Engines	SN-6D			1	2.32	9.2	5.9	3000	170	N	496	1063	
2	Yanmar	4JH-DTE	6.4	5.1	4	3.07	97.6	77	3600	173	T	309	2031	
3	Volkswagen	1.9L	2.8	2.7	4	3.13	115.7	110	4000	188	T	401	2507	Al.
4	Volkswagen	2.5L	2.9	2.7	5	3.19	150.2	140	4000	185	T	542	2507	Al.
5	Yanmar	4JH2-UTE	5.4	4.9	4	3.23	111.1	100	3600	198	T		2031	

APPENDIX F
Development of DOD-Specific Engine Family

The development of this engine family proceeded as described in Appendix D for the commercially based engine family. Again, a piston speed of 2300 fpm and a bore/stroke ratio of 1 were assumed. A smaller bore diameter of 2.75 in. was used for this family.

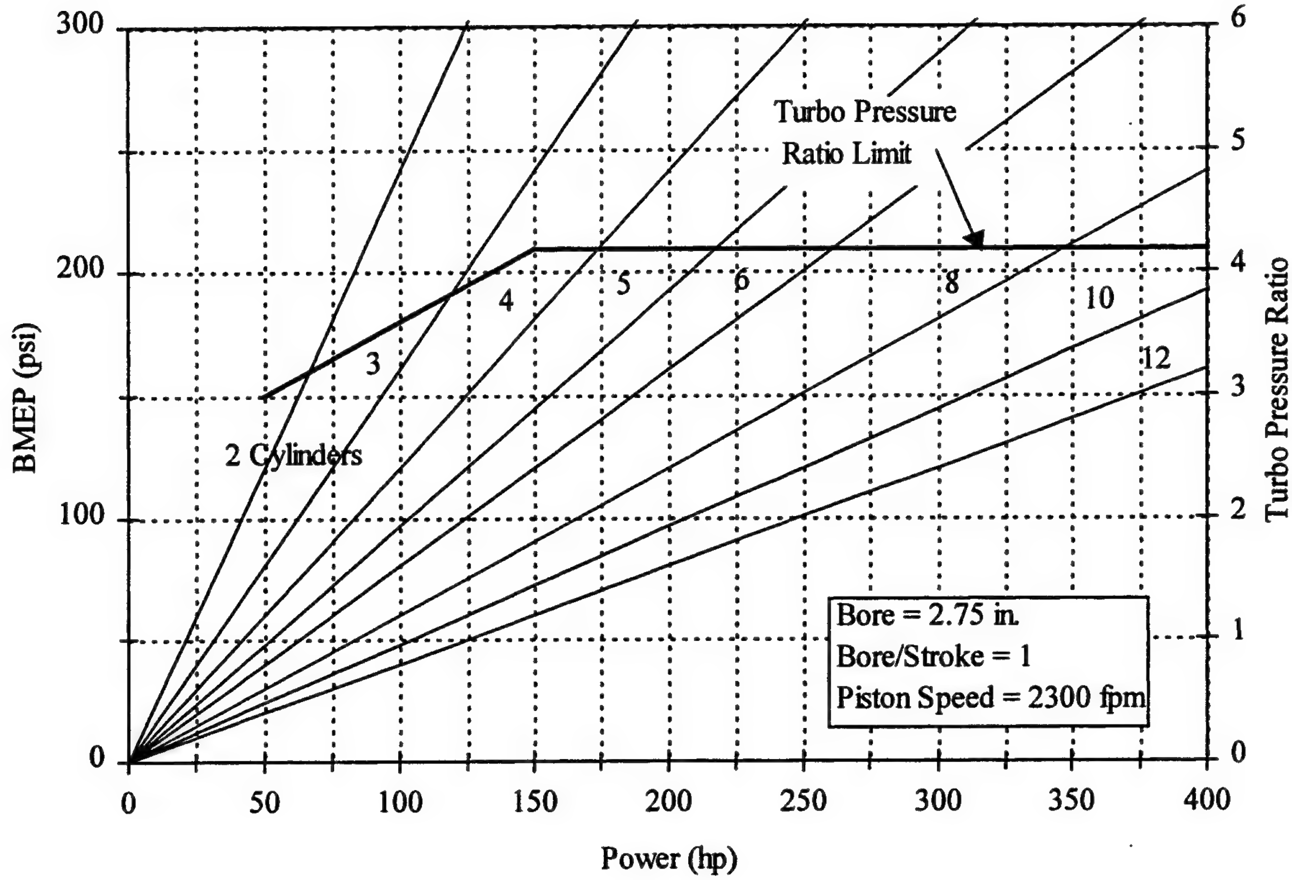

Figure F-1. **Plot of DoD-Specific Engine Family**

In addition, since this is a two-cycle engine family, the minimum volume-specific weight was assumed to be lower. Since no data was available for very small two-cycle diesel commercial engines, the value of 1.42 lb/in^3 was assigned to specific volume based on estimation of the weight reduction achievable using a two-cycle engine instead of a four-cycle engine. The resulting specific weights of this family are within the limits specified by DoD.

Table F-1. DoD-Specific Engine Family					
	Specified Power (bhp)	Specified Specific Wt. (lb/hp)	Resulting No. of Cyl.	Resulting BMEP (psi)	Resulting Specific Wt. (lb/hp)
UAV-High Endurance	120	1.67	3	195	0.59
UAV-Short Endurance	60	1.33	2	145	0.75
Motorcycle	40	1.88	2	100	1.12
Ship Fire Pump	30	1.5	2	75	1.5

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